Sensitivity of simulated mesoscale convective systems over East Asia to the treatment of convection in a high-resolution GCM

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Abstract

Mesoscale convective systems (MCSs) downstream of the Tibetan Plateau (TP) exhibit unique precipitation features. These MCSs can have damaging impacts and there is a critical need for improving the representation of MCSs in numerical models. However, most global climate models are typically run at resolutions that are too coarse to reasonably resolve MCSs, and it is still unclear how well higher-resolution global models can reproduce the precipitation characteristics of MCSs. In this study, the sensitivity of MCSs simulated by a global high resolution (~ 10km), atmosphere-only climate model to different treatments of convection (with and without parametrized convection, and a hybrid representation of convection) have been investigated. The results show that explicit convection (i.e., non-parameterized) can better reproduce the observed pattern of MCS precipitation over the East Asian Summer Monsoon (EASM) region. In general, explicit convection better simulates the diurnal variability of MCSs over the eastern China, and is able to represent the distinctive diurnal variations of MCS precipitation over complex terrain particularly well, such as the eastern TP and the complex terrain of central-northern China. It is shown that explicit convection is better at simulating the timing of initiation and subsequent propagating features of the MCS, resulting in better diurnal variations and further a better spatial pattern of summer mean MCS precipitation. All three experiments simulate MCS rainfall areas which are notably smaller than those in observations, but with much stronger rainfall intensities, implying that these biases in simulated MCS morphological characteristics are not sensitive to the different treatment of convection.

1. Introduction

Mesoscale convective systems (MCSs) are organized collections of precipitating cumulonimbus clouds and generally persist for several hours (Houze 2004, 2018). They play a vital role in regulating the hydrological and energy cycle, modulating the atmospheric circulation at both regional and global scales (Yuan and Houze 2010; Feng et al. 2016, 2021; Schumacher et al. 2020). MCSs can generate extreme rainfall and induce flash floods, severe winds, and even downbursts aligned with the intense deep convection (Zipser et al. 2006; Houze 2018; Song et al. 2019, 2021). Because of these damaging impacts, MCSs can cause heavy casualties and property losses.

The summer MCSs downstream of the Tibetan Plateau (TP) exhibit unique precipitation features due to the rugged underlying surface and a complex interplay with the large-scale monsoon circulations (Cui et al. 2020; Yang et al. 2020; Zhang et al. 2018), and long-lived MCSs are response for a majority of heavy precipitation and further cause catastrophic floods over the EASM (Chen et al. 2014, 2017; Guan et al. 2020). There is a critical need for improving the representation of MCSs in numerical models, in order to alleviate their damaging impacts (Prein et al. 2017a, b; Chen and Kirtman 2018; Feng et al. 2018). However, state-of-the-art global climate models cannot adequate resolve MCSs, owing to the insufficient model horizontal resolution and the large uncertainties derived from the parameterization of convection (Houze 2018; Prein et al. 2015), and the latter has been widely regarded as the dominant source of model biases in simulations of present-day precipitation and projections of future-precipitation changes (Liang et al. 2004; Dai 2006; Prein et al. 2015; Zhang and Chen 2016). Many long-standing simulated rainfall biases are associated with convection parameterizations, such as the errors of diurnal variations and excessive light precipitation (Dai 2006; Li et al. 2020a, 2021), not to mention the inaccurate simulation of MCSs (Bukovsky and Karoly 2010; Prein et al. 2017a, 2021). Therefore, contemporary large-scale numerical models with cumulus parameterization schemes cannot explicitly represent convective elements, nor reasonably reproduce the multiscale interactions within each individual MCS (Bukovsky and Karoly 2010; Kooperman et al. 2014; Yang et al. 2017; Chen and Kirtman 2018; Feng et al. 2018).

With the rapid development of computing resources, convection-permitting models (CPMs) with finer grid-spacing permit to resolve the deep convection in an explicit way and remove the reliance upon convection parameterization, which has been gradually applied to climate modelling in order to provide more reliable climate information (Prein et al. 2015, 2017c; Guo et al. 2019, 2020; Stevens et al. 2019, 2020). Prein et al. (2017a) found that their CPM can capture the general characteristics of an MCS over the east of the U.S., as well as its propagating features. Feng et al. (2018) used the Weather Research and Forecasting (WRF) at convection-permitting scales (WRF-CPM) to compare different cloud microphysics schemes (Morrison and Thompson) in simulating MCSs over the central U.S., they found that more simulated stratiform precipitation of the MCS in the Thompson microphysics parameterization can favor a relatively longer duration, through a stronger dynamical feedback to the larger-scale environments. Yun et al. (2021) investigated the performance of a WRF-CPM (~ 3km) over southern China in simulating the MCS properties, they found that the WRF-CPM can successfully reproduce the spatial pattern and seasonal march of MCS geneses and occurrences, but also demonstrated that the WRF-CPM overestimates the MCS occurrence and activities, therefore results in an overestimation of the contribution from MCSs to total precipitation. Guo et al. (2022) evaluated a WRF-CPM (~ 4km) over eastern China based on an object-based algorithm, and found that the WRF-CPM can well capture the duration and the eccentricity of precipitation systems, but the coverage area of the simulated systems are significantly larger with weak precipitation intensities.

Although the aforementioned analyses have discussed the performance of regional CPM in simulating precipitation characteristics of MCSs over the central U.S., as well as the eastern China, it is still unclear how faithfully a global high-resolution model under a convection-permitting configuration represents a climatology of MCS properties over the EASM domain, downstream of the highest and most extensive highland in the world—the TP. In addition, whether or not a convection-permitting configuration in a global model is better than a convection-parameterized configuration at grid spacing of O(10 km) in simulating the precipitation characteristics of MCSs still need to be answered.

To this end, we have investigated the sensitivity of simulated MCSs to the different treatment of convection in a high-resolution GCM (~ 10km) over the EASM, through applying a novel iterative rain cell tracking method to identify and track intense MCSs in CMORPH observations and three different configurations of high-resolution global Met Office Unified Model simulations.

The reminder of the article is organized as follows. Section 2 describes observation datasets, analysis methods, the experimental design and the model simulation we have used. Section 3 presents the main results, including the differences among three model configurations in simulating the summer mean MCS precipitation, as well as the precipitation characteristics of MCSs over the EASM. Finally, a brief summary and a discussion are given in Section 4.

2. Data And Methodology

2.1 Experimental design

By using global simulations, we perform our modelling with consistent physics at all scales and potentially capture phenomena such as mid-latitude and tropical interactions with the EASM in a physically consistent way. Our simulations are fully described in Muetzelfeldt et al. (2021), here we note the important aspects for this study. We make use of free running high-resolution global Met Office Unified Model simulations performed with three different configurations: fully parametrized convection (N1280-PC), fully explicit convection (N1280-EC) and hybrid convection (N1280-HC). The configuration for N1280-PC was HadGEM3-GC3.1 (Williams et al. 2018), with some minor modifications to allow it to be run at higher resolution. The boundary conditions, for e.g., sea surface temperature and aerosols, were based on the HighResMIP protocol (Haarsma et al. 2016). N1280-PC uses the standard Unified Model convection parametrization scheme (Williams et al. 2018).

N1280-EC has the shallow and deep convection parametrization schemes disabled, hence all moist convection is modelled by the model's internal dynamics and cloud physics schemes. N1280-HC has the deep convection scheme disabled but retains the shallow scheme. Both of these configurations use broadly the same settings as N1280-PC but have several other minor modifications for technical reasons and numerical stability (Muetzelfeldt et al. 2021). All three simulations were run for at least 4 years covering the period 2005–2008.

2.2 Observation dataset

We used the Climate Prediction Center's morphing technique (CMORPH; Joyce et al. 2004) satellite-retrieved precipitation product. This product covers the period studied here, from 2005 to 2008, with a horizontal grid spacing of approximately 8 km and a temporal resolution of 30 minutes. In this study, we convert the original 30min temporal resolution product into an hourly precipitation product, and mainly focused on the MCS precipitation over East Asia in boreal summer (June-July-August). To enhance the comparison between the CMORPH satellite retrievals and the three HadGEM3-GC3.1 simulation, we re-grid the CMORPH product onto the model grid, then apply the iterative raincell tracking method and conduct follow-up analysis.

2.3 Iterative Raincell Tracking method

We use the precipitation variable to identify MCSs in the CMORPH observations and simulations. The MCS tracking approaches used in this study are similar to the previous studies, such as Davis et al.

(2009), Clark et al. (2014) and Prein et al. (2017a, b). These approaches align well with the MCS definition proposed by Houze (2004), which identified a MCS as continuous precipitation areas (having a typical diameter longer than 100km in at least one direction) that live for a few hours.

In this study, we identify and track MCSs in space and time by using an “iterative raincell tracking (IRT)” technique (Moseley et al. 2013, 2019; Li et al. 2020b). For each time step independently, connected areas with surface precipitation exceeding a predetermined threshold are recognized as objects in the first step. The weighted center, rainfall area, and mean/max surface precipitation intensity within the rainfall area are all recorded for each labelled object. An MCS is defined as a single entity with intense precipitation ($\geq$ 3.0 mm h^{-1}) covering an area larger than 3,600 km^2, and lasting at least two hours. This threshold is set to exclude too small and non-MCS storms, thus allows us to track intense storms with relatively enough size, which follows the same threshold settings in the previous study of Li et al. (2020b). Additional sensitivity tests using 5.0 mm h^{-1} and 2.5 mm h^{-1} have demonstrated that while the changing thresholds will impact the amount of discovered MCS, the overall MCS features remain robust and do not change the conclusions revealed in this study. Here we focus on the sensitivity of different treatment of deep convection in simulating intense MCSs because of their high socioeconomic importance.

The method looks for overlaps between each object with objects from the previous and subsequent time steps, and saves the object IDs associated with those overlaps. In terms of handling of merging and fragmentation incidents: if an object overlaps with more than one object in a previous or subsequent time step, only the two biggest objects are recorded; the other objects are disregarded. A convergent iterative algorithm repeats the object identification numerous times to account for the fact that objects move over time, more details of the convergent iterative algorithm can be found in Moseley et al. (2019) and Li et al. (2020b). Each succeeding iteration step estimates the object’s advection velocity and incorporates it into the future iteration's detection procedure. Finally, overlapping objects are integrated into a single track.

3. Results

3.1 Performance in simulating total EASM precipitation

We first investigate the performance of different configurations of HadGEM3-GC3.1 at the O(10km) grid spacing in simulating the summer mean precipitation over the EASM region (Fig. 1). In general, all three observational datasets (i.e., the CMORPH, TRMM and GPCP) agree well with each other regarding the spatial distribution of summer mean precipitation (Fig. 1a-c). There are three rainfall centers over the EASM region (the summer rainfall located in South China Sea is neglected in this study): one is located over southeastern China, the second rain-belt is named as the “Mei-yu” (in China) and “Chang-ma” (in South Korea), and the third one is called the “Bai-u” (in Japan) which is located in the southern Japan.

The three HadGEM3-GC3.1 simulations generally agree with the observation, but there are also some deficiencies in each simulation: N1280-EC can well reproduce the spatial distributions of the observed precipitation, but it overestimates precipitation over southeastern China and underestimates the “Mei-yu” and “Chang-ma” rain-belt, as well as underestimating the precipitation over southern Japan (Fig. 1d); Both the N1280-HC (hybrid version) and the N1280-PC (fully-parameterized version) underestimate the precipitation within the “Mei-yu” and “Chang-ma” rain-belt, but better represent the magnitude of precipitation over southern Japan (Fig. 1e and 1f).

3.2 Sensitivity to different treatment of convection in simulating MCS precipitation

3.2.1 Summer MCS tracks and the spatial distribution of summer mean MCS precipitation

We further check the sensitivity to different treatment of convection (explicit .vs. hybrid .vs. fully-parametrized) in simulating MCS precipitation at the O(10 km) grid spacing. All MCS tracks among observations and simulation are shown in Fig. 2. A total of 3370, 3493, 2499 and 2630 intense MCS precipitation systems over the EASM region were tracked in CMORPH, N1280-EC, N1280-HC and N1280-PC, respectively. It should be noted that the N1280-EC (Fig. 2b) has slightly more MCSs than observed (+ 3.6%), but both the N1280-HC (-25.8%; Fig. 2c) and the N1280-PC (-22.0%; Fig. 2d) have considerably fewer MCS tracks compared with those observed in CMORPH (Fig. 2a).

The spatial distributions of MCS precipitation among observations and simulation are shown in Fig. 3. There are three main MCS precipitation centers over the EASM region, in accordance with the summer total precipitation: one rainfall center is located over southeastern China, one center is the southwest-northeast-elongated rain belt, which is called “Mei-yu” in China and “Chang-ma” in South Korea, and the third one is located in southern Japan (Fig. 3a).

N1280-HC and N1280-PC fail to properly reproduce the spatial distributions of the summer MCS precipitation over the EASM domain (Fig. 3c and 3d), with a relatively lower pattern correlation coefficients (PCCs) of 0.65 and 0.61, and a higher root-mean-square errors (RMSEs) of 1.45 mm day^{-1} and 1.48 mm day^{-1}, respectively. Specifically, they cannot simulate the precipitation over southeastern China (Fig. 3c and 3d), and underestimate the summer MCS precipitation within the “Mei-yu” and “Chang-ma” rain-belt (Fig. 3c and 3d). However, they better simulate the MCS precipitation over southern Japan (Fig. 3c and 3d). Another interesting feature is that the MCS precipitation in the N1280-HC and N1280-PC is anchored by the topography along the so-called “second-step” to “third-step” terrain region (the region where the 300, 600, 900m topography contours become denser around 32°~40°N) over eastern China (Fig. 3c and 3d), which indicates that the precipitation enhancement -effects of the topography are magnified in these two model configurations; this will be specifically discussed in the later section 3.2.2. The overestimation of precipitation along the steep terrain region is smaller in N1280-HC (Fig. 3c), compared with those in N1280-PC (Fig. 3d).

Among three different model configurations, N1280-EC best reproduces the observed pattern of MCS precipitation (Fig. 3b), with a higher PCC of 0.72 and a lower RMSE of 1.37 mm day^{-1}, compared with

N1280-HC and N1280-PC. It well simulates the MCS precipitation center over the southeastern China, as well as better reproduces the “Mei-yu” and “Chang-ma” rain-belt (Fig. 3b). However, it still has some obvious deficiencies: it overestimates the MCS precipitation over southeastern China but underestimates the magnitude of “Mei-yu” and “Chang-ma” rain-belt, as well as the MCS precipitation over southern Japan (Fig. 3b).

3.2.2 The diurnal cycle of MCS precipitation

The diurnal cycle of convective precipitation exhibits some interesting behavior over the EASM region, such as a phase delay running east-west along the Yangtze River (Yu et al. 2007, 2015; Chen et al. 2010). As such, the diurnal cycle represents a rigorous test-bed for validating convection parametrizations and other physical schemes in numerical models (Yuan et al. 2013; Zhou et al. 2018; Li et al. 2020a). In this study, one of the most remarkable differences among the three model configurations is the different diurnal variations of the MCS precipitation over the EASM region (Fig. 4 and Fig. 5). In observations, the diurnal variations of MCS precipitation over the eastern periphery of the Tibetan Plateau (ETP) are dominated by the nocturnal precipitation (Fig. 4a and Fig. 5a), which is due to the low-level moisture transport increasing after sunset and reaching its maximum before dawn, similar with the diurnal variations of the total precipitation which have been documented in previous studies (Chen et al. 2010; Chen et al. 2014; Zhang et al. 2019; Muetzelfeldt et al. 2021). It should be noted that there is a marked regional difference over this steep terrain region. To the west of the ETP, it is the late-afternoon precipitation that dominates the diurnal variations at higher altitudes (regions where the topography exceeds 2700m) over the TP (Fig. 4a), which is quite different from the nocturnal/morning peak at lower altitudes (i.e., the Sichuan Basin) within the ETP region (Li J et al. 2021).

All HadGEM3-GC3.1 simulations well simulate the nighttime MCS precipitation over the ETP (Fig. 4b-d), although with a stronger magnitude (Fig. 5a). However, N1280-PC cannot reproduce the late-afternoon MCS precipitation at higher altitude regions over the TP, it produces more nocturnal rainfall at higher altitudes over the TP than the observed, and therefore incorrectly reproduces the distinct regional features of the diurnal variations over this complex terrain region (Fig. 4d). In contrast, N1280-EC and N1280-HC better reproduce the late-afternoon MCS precipitation at higher altitudes over the TP.

In CMORPH, the diurnal variations of MCS precipitation in the monsoonal “Mei-yu” and “Chang-ma” rain-belt are dominated by the early morning diurnal peaks (Fig. 4a), because of the early-morning acceleration of the low-level monsoon flow and the subsequent strengthening of its convergence (Chen et al. 2013, 2017; Guan et al. 2020). The MCS precipitation in the middle-to-lower reaches of the Yangtze River basin (YRB-ML) in eastern China exhibits two diurnal peaks: one is the early-morning peak; the other one is the late-afternoon rainfall peak (Fig. 4a and Fig. 5b), which is associated with more “surface-driven” intense MCS precipitation that occurs beyond the large-scale monsoonal rain-belt and become predominantly active during the “break” monsoon periods, based on previous studies (Yuan et al. 2010; Yu et al. 2014; Yu and Li 2015). The MCS precipitation over the southeastern China (SEC) shows two weak diurnal peaks in observations (Fig. 4a and Fig. 5c): one primary peak during late-afternoon (1600 ~ 1800 LST) and a secondary peak in the nighttime to early-morning (0200 ~ 0800 LST). The MCS precipitation over the lower reaches of the Yellow River basin (LYB) exhibits two comparable diurnal peaks (Fig. 4a and Fig. 5d).

In the simulations, N1280-HC and N1280-PC both overestimate the magnitude of nighttime MCS precipitation over the YRB-ML (Fig. 5b) and LYB (Fig. 5d). A consistent model bias of N1280-HC and N1280-PC (especially N1280-PC) is that there is a 3 ~ 5 hours delayed phase in simulating the late-afternoon MCS precipitation peak over mainland eastern China (observed at 1600 ~ 1800LST), including the YRB-ML, the SEC, as well as the LYB (Fig. 5b-5d). In addition, N1280-HC and N1280-PC cannot simulate the diurnal variations of the MCS precipitation over the central north China. Specifically, both N1280-HC and N1280-PC (Figure. 4c and 4d) cannot reproduce the northwest-to-southeast delayed phase from mountain to plain along around the 40 ° N (Figure. 4a), which will be discussed in more detail in section 3.2.3.

In contrast, N1280-EC better simulates the diurnal variations of MCS precipitation over the YRB-ML (Fig. 5b), SEC (Fig. 5c), as well as LYB (Fig. 5d), particularly for the phase of the peaks. Furthermore, N1280-EC reproduces the diurnal variations of the MCS precipitation over central north China (Fig. 4a and 4b), which indicates that the explicit convection version can reproduce the initiation as well as the propagating features of the MCSs, which generally form over the mountain regions in the afternoon, then propagate downstream at night, inducing heavy rainfall.

The results here are consistent with and complementary to those of Muetzelfeldt et al. (2021), who analysed the same simulations and found that the summertime diurnal cycle of total precipitation over Asia was best simulated in model configurations without parameterized convection. Furthermore, they found that the diurnal variations only improved at finer resolution in simulations without parameterized convection. As MCSs are relatively fine-scale phenomena, it is therefore consistent that the diurnal cycle of their precipitation should be improved in models with explicit convection. Here, we have looked at a dynamical phenomenon, and so our results show that the general findings of Muetzelfeldt et al. (2021) apply to specific features, MCSs, over Asia. This could be interpreted in two ways – these are not necessarily mutually exclusive. First, the improved diurnal cycle at large (synoptic) scales leads to a corresponding improvement in the diurnal cycle at smaller scales, including that of MCSs. Second, the improved representation of MCSs, as shown above in Sect. 3.2.1 showing the number of simulated MCSs, leads to an upscale improvement in the diurnal cycle. In our view, the first of these is most likely, although further work would be required to disentangle these two effects.

3.2.3 Properties of observed and simulated MCSs over the EASM

After evaluating the model differences in simulating the diurnal variations of the MCS precipitation, the MCS statistical properties, including MCS lifetime, rainfall area, average/ maximum hourly precipitation over four sub-regions among CMORPH and simulation are shown in Fig. 6. In general, all three different configurations agree well with the CMORPH in terms of the MCS duration (Fig. 6a), but the MCS in the

N1280-HC simulation has relatively longer duration, compared with other two configurations and CMORPH (Fig. 6a).

The most distinct differences between the CMORPH and HadGEM3-GC3.1 simulation are in the rainfall area (Fig. 6b) and intensity (Fig. 6c and 6d) of the MCSs. The MCSs in the all the three different configurations of HadGEM3-GC3.1 simulations have a notably smaller rainfall area (Fig. 6b), but with a much stronger rainfall intensity (both the average and maximum hourly precipitation; Fig. 6c and 6d), compared with CMORPH. This indicates that the model behaviors relating to the spatial morphological characteristics (such as the rainfall area and intensity) of MCS precipitation systems might not be sensitive to the different treatment of convection, and should be attributed to other key elements or parameterizations in the model, for instance the evolution of density currents in the boundary-layer parameterization as in Jucker et al. (2020).

We proceed to investigate the performance of the three model configurations in simulating the dynamical evolution of long-lived MCS precipitation characteristics (MCS rainfall area: Fig. 7; maximum hourly precipitation: Fig. 8) over eastern China from a statistical standpoint. It should be noted that the solid line in Fig. 7 and Fig. 8 indicates the mean of MCSs to represent the general features of the dynamic evolution of MCS precipitation properties, and the shadings indicates the interquartile range across all MCSs.

In general, the three different configurations can partly reproduce the dynamical evolution of the MCS rainfall area, but with a systematic underestimation during almost the whole lifetime, among all four sub-regions (Fig. 7a-7d). The MCS rainfall area in the HadGEM3-GC3.1 simulations increases more slowly in the developing stage and does not grow to a large-enough size at mature stage, compared with that in CMORPH (Fig. 7). Over the YRB-ML, the MCS rainfall area in all three HadGEM3-GC3.1 simulations persists for longer than in CMORPH (Fig. 7b), consistent with the longer MCS duration over the YRB-ML in the simulation (Fig. 6a). Among all three model configurations, the MCS rainfall area in N1280-HC persists relatively longer over ETP (Fig. 7a), YRB-ML (Fig. 7b), as well as LYB (Fig. 7d), compared with those in the CMORPH and other two configurations.

There exists an obvious asymmetry in the dynamical evolution of the MCS maximum hourly precipitation (Fig. 8). The MCS rainfall intensity increases quickly, reaching its peak intensity during the developing stage (Fig. 8). This kind of intense convective precipitation is related to the strong updrafts within an MCS when the precipitating cumulonimbus clouds aggregate and develop. Then the MCS rainfall intensity gradually weakens with a slower rate for the remainder of the MCS's lifetime (Figure. 8). This kind of relatively moderate stratiform precipitation is induced by large-scale condensation when the updrafts become weaker and cannot support vertical advection of precipitation particles. All three model configurations of the HadGEM3-GC3.1 can generally reproduce the asymmetry in the development of MCS rainfall intensity, but the maximum hourly precipitation intensity in the simulations is about three times higher than in CMORPH.

3.2.4 Different model behaviors in simulating summer MCS precipitation over complex terrain

There is a distinct difference among the three configurations in simulating summer MCS precipitation over complex terrain. Here this difference is illustrated for a region in central north China, and the underlying physical mechanisms are investigated.

The spatial distributions of summer MCS precipitation over central north China, as well as their diurnal variations are shown in Fig. 9 and Fig. 10. A consistent model bias in N1280-PC is that the excessive MCS precipitation is anchored by steep terrain: too much MCS precipitation is concentrated at the mountain slope, the areas where the topography is between the 300m and 600m (Fig. 9d). Additionally, the magnitude of the “Mei-yu” and “Chang-ma” rain-belt is significantly underestimated in N1280-PC, especially the MCS precipitation over the lower-to-middle reaches of the Yangtze River basin in China, as well as the MCS precipitation over South Korea. Therefore, N1280-PC has relatively lower skill over in simulating the spatial pattern of the MCS precipitation over central north China and its surroundings, with a low PCC value of 0.41 and a high RMSE value of 1.59 mm day^{-1} (Fig. 9d). The overestimation of the summer MCS precipitation along steep terrain is partly reduced in N1280-HC (Fig. 9c), which might indicate a benefit from using a hybrid convection scheme, but similar kinds of model bias were also found in this model configuration. Thus N1280-HC has moderate skill in simulating the MCS precipitation pattern, with a PCC value of 0.57 and a RMSE value of 1.33 mm day^{-1}.

A step-change improvement was found between N1280-HC to N1280-EC (from Fig. 9c to 9b), when the convection parametrization scheme is completely disabled. The excessive MCS precipitation over the steep terrain region has been mostly eliminated, and the “Mei-yu” and “Chang-ma” rain-belt are much better depicted (Fig. 9b). As a result, the N1280-EC has higher skill in reproducing the spatial distributions of the MCS precipitation, with a higher PCC value of 0.76 and a lower RMSE value of 0.98 mm day^{-1}.

We further investigated the diurnal variations and propagating features of the summer MCS precipitation over central north China in CMORPH observations and three simulations (Fig. 10 and Fig. 11). In CMORPH, the MCS precipitation initializes and enhances over the northwestern mountainous region in the late-afternoon (Fig. 10c), thereafter the organized convection propagates to the lower altitudes, i.e., the southeastern plains (Fig. 10d and 10e). The diurnal variations of MCS precipitation are related to the MCS propagating features, as shown by the averaged moving direction and speed of MCSs in Fig. 11. The observed MCSs move eastward from northwestern mountainous region to the southeastern plain with velocities of 35 ~ 40 km h^{-1} (Fig. 11a), resulting in intriguingly pronounced spatial distributions of the MCS diurnal variations associated with the topography, where an obvious delayed phase can be seen from northwestern mountains to southeastern plains (Fig. 9e). Following sunrise, the MCS precipitation over the mountains rapidly decreases (Fig. 10f), and reaches a minimum around local noon (Fig. 10a).

N1280-PC cannot accurately reproduce the late-afternoon MCS precipitation over the northwestern mountain (Fig. 10u), nor can it simulate the propagating features of the MCS precipitation (Fig. 10v). In contrast, too much MCS precipitation is seen at lower altitudes following the steep terrain (Fig. 10u), whereas too little MCS precipitation is seen over the northwestern mountainous region where it should occur (Fig. 10c). The excessive MCS precipitation center at lower altitudes in the steep terrain persists throughout the night (Fig. 10v-10x), and continues to exist even after sunrise (Fig. 10s and 10t). These phenomena are also reflected in the averaged MCS propagation direction and speed (Fig. 11). In N1280PC, there are much more MCSs at lower altitudes alongside the steep terrain, and the MCSs remain quasi-stationary with a much lower propagation speed (Fig. 11d), compared to those in CMORPH observations (Fig. 11a). Therefore, the summer MCS precipitation in N1280-PC exhibits inaccurate diurnal variations (Fig. 9h) and distinct wet biases related to the complex terrain over central north China (Fig. 9d).

In N1280-HC, the excessive night MCS precipitation at lower altitudes along the steep terrain is not as pronounced as that in N1280-PC (Fig. 10o-10r), but the MCS in N1280-HC still preferentially occurs and exhibits a quasi-stationary propagating feature at lower altitudes along the steep terrain (Fig. 11c), and the summer MCS precipitation remains active throughout the day (Fig. 10m-10r), thus leading to a similar wet bias of the summer MCS precipitation in N1280-HC (Fig. 9c).

In contrast to N1280-PC and N1280-HC, N1280-EC can better reproduce the late-afternoon MCS precipitation over mountainous region (Fig. 10h and 10i), as well as represent the propagating features of the organized convection systems from late-afternoon to night (Fig. 10j and 10k). In addition, N1280-EC reasonably simulates the direction and speed of the summer MCS propagating features (Fig. 11b), and better depicts the underlying diurnal variations of MCS precipitation over central north China (Fig. 10g-l and Fig. 9f). As a result, N1280-EC better simulates the spatial distribution of the summer MCS precipitation over this complex terrain region (Fig. 9b) and closely resembles CMORPH (Fig. 9a).

4. Summary And Discussion

4.1 Summary

In this study, we have used an iterative rain cell tracking method to identify and track intense MCSs in CMORPH observations and three model configurations of HadGEM3-GC3.1 (fully-explicit convection: N1280-EC, hybrid convection: N1280-HC and fully-parametrized convection: N1280-PC) at the O(10 km) grid spacing. We have investigated the sensitivity of simulated MCS precipitation over East Asia to the treatment of convection in this model, the major findings are summarized as below:

It is found that N1280-HC and N1280-PC have considerably fewer MCS tracks over the East Asia, with an underestimation of -25.8% and − 22.0%, compared with those in CMORPH. N1280-EC has a similar number of MCS tracks to those in CMORPH, with a slight overestimation of + 3.6%. The setting of explicit convection therefore demonstrably improves the number of MCS events.

There are three main MCS precipitation centers over the EASM, which are not well represented in N1280-PC and N1280-HC simulations. For instance, they cannot simulate the precipitation over southeastern

China, and underestimate the MCS precipitation within the “Mei-yu” and “Chang-ma” rain-belt. N1280-HC and N1280-PC have relatively lower PCCs of 0.65 and 0.61 compared with CMORPH, and higher RMSEs of 1.45 mm day^{-1} and 1.48 mm day^{-1}, respectively. In contrast, N1280-EC can better reproduce the observed pattern of MCS precipitation. It is better at simulating the MCS precipitation center over the southeastern China, and better at reproducing the “Mei-yu” and “Chang-ma” rain-belt, and thus has a higher PCC of 0.72 and a lower RMSE of 1.37 mm day^{-1} compared with other two model configurations. Hence, N1280-EC is demonstrably better at representing the geographical distributions of MCS precipitation over the EASM, although it overestimates the MCS precipitation over southeastern China.

One of the most remarkable differences among three model configurations is the different diurnal variations of the MCS precipitation. In general, N1280-HC and N1280-PC both overestimate the magnitude of nighttime MCS precipitation over the YRB-ML and LYB. A consistent model bias of these two versions (especially N1280-PC) is that they have a 3 ~ 5 hours delayed phase in simulating late-afternoon MCS precipitation peak over mainland eastern China. In comparison, N1280-EC better simulates the diurnal variations of MCS precipitation over the YRB-ML, SEC and LYB. We also found that N1280-EC can better represent the distinct diurnal variations over complex terrain, such as the regions surrounding the eastern periphery of the Tibetan Plateau (higher mountains .vs. lower valleys), as well as over the complex terrain of central north China. This indicates that N1280-EC is better at reproducing the timing of initiation and subsequent propagation of the MCS precipitation, resulting in a better diurnal variations.

The difference in simulating diurnal variations is also reflected in the summer mean MCS precipitation over regions with complex terrain. A detailed investigation focusing on central north China showed that the diurnal variations of MCS precipitation are related to the MCS propagating features in the CMORPH. The observed MCS initializes and enhances over the northwestern mountains in the late-afternoon and then propagates to the southeastern plain downstream with velocities of 35.0 ~ 40.0 km h^{-1}, resulting in a pronounced delayed phase from northwestern mountains to southeastern plains in the diurnal variations over central north China. An excessive MCS precipitation in N1280-PC is anchored to the low altitudes alongside steep terrain, and too much MCS precipitation is concentrated in the areas between the 300m and 600m contours, which mainly result from the incorrect diurnal variations induced by the deep convection scheme. This leads to a lower skill in simulating the spatial distributions of the summer MCS precipitation over central north China. N1280-HC has moderate skill, and a step-change improvement was found in N1280-EC. In this model, appropriate propagating features and realistic diurnal variations result in a more accurate simulation of the geographical distributions of summer mean MCS precipitation over the complex terrain in central north China.

The MCS statistical precipitation properties have been also investigated. All three simulations agree well with the CMORPH regarding the MCS duration. An interesting aspect is that the simulated MCSs in all three simulations have a notably smaller rainfall area but a much stronger rainfall intensity (both the average and maximum hourly precipitation) than those seen in CMORPH. This result indicates that the model behaviors on the morphological characteristics (such as rainfall area and precipitation intensity) of MCS is not sensitive to the different treatment of convection in these simulations. There should be some other key elements or parameterizations that result in these biases. For instance, the evolution of density currents in the boundary-layer parameterization according to a previous study (Jucker et al. 2020), the number of prognostic moments in the cloud microphysics scheme, or the insufficient model horizontal resolution.

4.2 Discussion

A convection parameterization scheme acts to remove atmospheric instability because of its representation of the effect of all the cumulus clouds at the grid scale. Consequently, feedbacks between large-scale forcings and finer-scale dynamics will be broken. Given that MCSs are inherently a combination of cumulus and mesoscale dynamics, coupled to the underlying thermodynamic changes associated with the phase change of water, it is plausible that they should be adversely affected by the use of a convection parameterization scheme; here we have shown that this is the case for the total number of simulated MCSs (Sect. 3.2.1) and the diurnal variations and propagation of MCS precipitation (Sect. 3.2.2) in a O(10km) global climate model. This has an important consequence: if the representation of MCS and its remote drivers is important (e.g., to represent extremes in rainfall), it would be desirable to use an explicit-convection simulation and a global setup. The simulations investigated in this study are promising in this regard but currently have substantial mean-state biases in Asian precipitation, thus tuning of these simulations should be a priority (Muetzelfeldt et al. 2021).

Declarations

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Author contributions:

All the authors made contributions to the conception or design of the research. PL did the analyses and drafted the work and others contributed to the revising and editing of the paper. MM, RS and KF conducted the global high-resolution simulations including N1280-EC, N1280-HC and N1280-PC. HC and JL acquired the funding and supervised the research.

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Availability of data and material:

The high-resolution global Met Office Unified Model (N1280) simulation output data are available upon request, as each simulation is over 80 TB in size and stored on the Met Office Managed Archive Storage System (MASS). CMORPH data are available from ftp://ftp.cpc.ncep.noaa.gov/precip/CMORPH_V1.0/CRT/8km-30min/.

Code availability:

This study used NCL (NCAR Command Language) and CDO (Climate Data Operators) software. NCL is an open source interpreted language, designed specifcally for scientific data visualization and processing. CDO is a collection of many operators for standard processing of climate and forecast model data. Both are freely available at http://www.ncl.ucar.edu and http://www.mpimet.mpg.de/cdo, respectively.

Conflicts of interest:

The authors declare that there is no conflict of interest.

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Tables

Table 1.

The number of MCS tracks over the East Asian Summer Monsoon (EASM) region, as well as the minimum and maximum duration of the MCS among the CMORPH, N1280-EC, N1280-HC and N1280-PC simulation.

	The number of MCS tracks over the EASM region	The minimum and maximum of MCS duration among OBS and simulation (unit: hours)	
		Min.	Max.
CMORPH	3370	2	117
N1280-EC	3493	2	97
N1280-HC	2499	2	159
N1280-PC	2630	2	86

Figures

Figure 1

Spatial distributions of summer total precipitation from 2005 to 2008 in observation and simulation: (a) CMORPH, (b) TRMM 3B42, (c) GPCP_1dd, (d) N1280-EC, (e) N1280-HC, and (f) N1280-PC. Here blue lines indicate the Yellow River and Yangtze River, respectively, and the red contour indicates the TP where the topography exceeds 2700 m.

Figure 2

Summer mesoscale convective system (MCS) tracks from 2005 to 2008 in observation and simulation: (a) CMORPH, (b) N1280-EC, (c) N1280-HC, and (d) N1280-PC. Here blue lines indicate the Yellow River and Yangtze River, respectively, and the red contour indicates the TP where the topography exceeds 2700 m.

Figure 3

Spatial distributions of MCS precipitation (unit: mm day^{-1}) from 2005 to 2008 in observation and simulation: (a) CMORPH, (b) N1280-EC, (c) N1280-HC, and (d) N1280-PC. Here blue lines indicate the Yellow River and Yangtze River, respectively, and the red contour indicates the TP where the topography exceeds 2800 m. The white contours represent surface elevation (unit: m), where 300, 600, 900, 1200, 2700m contours are drawn.

Figure 4

Spatial distributions of the local solar time (hereafter "LST" in short; colored) of the maximum (T_{max}) in the composite diurnal cycle of the summer MCS precipitation frequency over the East Asia among observations and simulations: (a) CMORPH, (b) N1280-EC, (c) N1280-HC and (d) N1280-PC. Here the orange rectangle (middle-left) indicates the eastern periphery of the Tibetan Plateau, the blue rectangle (middle-right) indicates the middle-to-lower reaches of the Yangtze River Basin, the red rectangle (bottom) indicates southeastern China and the pink rectangle (top-right) indicates the lower reaches of the Yellow River Basin. The white contours represent surface elevation (unit: m), where 300, 600, 900, 1200, 2700m contours are drawn.

Figure 5

Diurnal variations of summer mean MCS precipitation averaged over different sub-regions in Eastern China: (a), the eastern periphery of the Tibetan Plateau (ETP; 27.0°N-34.0°N, 102.5°E-110.5°E); (b) the middle-to-lower reaches of the Yangtze River Basin (YRB-ML; 27.0°N-33.0°N, 110.5°E-121.5°E), (c) southeastern China (SEC; 21.0°N-27.0°N, 102.5°E-117.5°E) and (d) the lower reaches of the Yellow River Basin (LYB; 33.0°N-38.0°N, 110.5°E-120.0°E) among observations and model simulations (unit: mm day^{-1}). Here the black, red, blue and oranges lines indicate the observation, N1280-EC, N1280-HC and N1280-PC simulation, respectively.

Figure 6

Overall MCS statistical characteristics over four sub-regions among observations and model simulations: (a) MCS duration (unit: hours), (b) MCS rainfall area (unit: 10^2 km^2), (c) MCS average hourly precipitation (unit: mm h^{-1}), (d) MCS maximum hourly precipitation (unit: mm h^{-1}). Here the black, red, blue and oranges lines indicate CMORPH, N1280-EC, N1280-HC and N1280-PC, respectively. In the boxplot, the horizontal bars denote the medium values, the boxes indicate the interquartile range (25% and 75%), and the whiskers represent 10% and 90% percentile values.

Figure 7

Development of long-lived (duration 6hours) MCS rainfall area as a function of MCS age in CMORPH (black) and model simulation (red: N1280-EC; blue: N1280-HC; orange: N1280-PC) over four sub-regions: (a) ETP, (b) YRB-ML, (c) SEC, and (d) LYB. Here the shadings/error bars show the interquartile spread in each sample, the solid line shows the medium values. The x-axis indicates the MCS age (unit: hour), the y-axis indicates MCS rainfall area (unit: 10^4 km^2).

Figure 8

Same as Figure 7, but for the development of MCS maximum hourly precipitation as a function of MCS age (unit: mm h^{-1}).

Figure 9

Spatial distributions of summer MCS precipitation (unit: mm day^{-1}) and the maximum phase in the diurnal variations of the summer MCS precipitation frequency over the central north China and its surrounding regions: (a) CMORPH, (b) N1280-EC, (c) N1280-HC, and (d) N1280-PC. The white contours represent surface elevation (unit: m), where 300, 600, 900, 1200m contours are drawn. The blue lines indicate the Yellow River and Yangtze River, respectively.

Figure 10

Diurnal variations of every 4-hr (0800-1100LST, 1200-1500LST, 1600-1900LST, 2000-2300LST, 0000-0300LST and 0400-0700LST) accumulated summer precipitation (unit: mm day^{-1}) over the central north China and its surrounding regions among (a-f) CMORPH, (g-l) N1280-EC, (m-r) N1280-HC and (s-x) N1280-PC. The purple contours represent surface elevation (unit: m), where 300, 600, 900, 1200m contours are drawn.

Figure 11

The averaged MCS propagation direction and speed (vectors; unit: km h^{-1}), and the number of summer MCSs (shadings) within each 1° 1° grid box during the study period over the central north China and its surrounding regions among (a) CMORPH, (b) N1280-EC, (c) N1280-HC and (d) N1280-PC. Here the black contours represent surface elevation (unit: m), where 300, 600, 900, 1200m contours are drawn.